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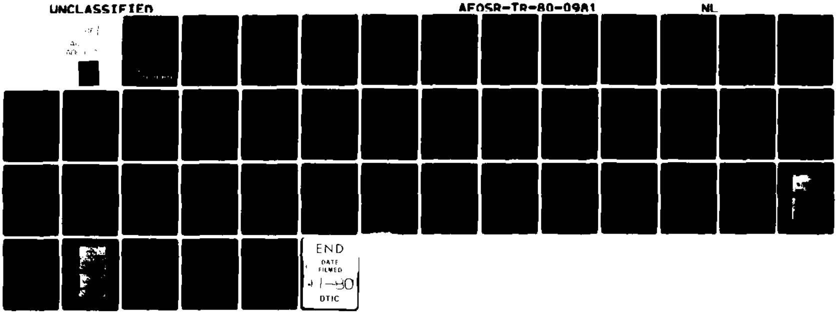

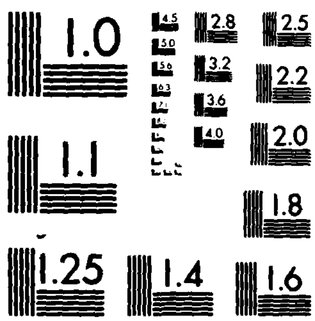

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Final Report
on

DENSE PLASMA HEATING AND RADIATION GENERATION

Period Covered: January 1, 1974 - April 30, 1980

Research Grant AFOSR 74-2639
and AFOSR 79-0034

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The research conducted consisted of three related studies of the interaction of a laser with plasmas and solids. These studies were: 1) experimental and theoretical investigations of laser-plasma interactions, 2) experimental investigations of nonlinear optical mixing in a dense plasma, and 3) experimental investigations of solid-laser-plasma interactions. In addition, a survey was made of pulsed power techniques. A computer code has been developed to predict the interaction of a focused or collimated laser beam with a dense, fully ionized, hydrogen plasma. A laboratory constructed plasma source was designed and

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constructed to test the validity of this code. The agreement was good. The nonlinear optical mixing experiment consisted of focusing two different frequency CO_2 laser beams, with the difference frequency equal to the plasma frequency, into a dense, preformed, helium plasma. Theory predicts this to be a viable method of heating a plasma. The results were informative, but indicated that this heating method only is useful under very stringent plasma parameter controls. In the laser-plasma-pellet experiment, a ruby laser was focused onto a polystyrene pellet positioned in a dense theta pinch plasma. The gas cloud ablated by the plasma and laser was studied, along with the effects on the pellet. A comparison with theory was also made. The agreement was, again, good. The survey of pulsed power techniques was made to provide a reference source for some of the important concepts in this field.

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6 DENSE PLASMA HEATING AND RADIATION GENERATION

10 M. Kristiansen [redacted] M.O. Hagler

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3. Mr. E.Y. Chu: Research Assistant
4. Mr. R.L. Druce: Research Assistant
5. Mr. L.B. Gordon: Research Assistant
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1. December 1974, W.C. Nunnally, Ph.D.: "High Temperature Theta Pinch Plasma Interaction With a Solid Pellet".
2. December 1974, J.E. Thompson, Ph.D.: "Optical Measurements of High Electric and Magnetic Fields.
3. May 1975, D.L. Smith, M.S.E.E.: "Thomson Scattering Diagnostics of the Teepee IA Theta Pinch."
4. December 1975, R.L. Druce, M.S.E.E.: "Computer Simulation of Laser-Plasma Interaction in a Magnetic Field."
5. December 1976, J.F. Francis, M.S.E.E.: "High Voltage Pulse Techniques".
6. May 1977, J.S. Jasper, M.S.E.E.: "An Electron Beam Controlled CO_2 Laser".
7. December 1977, D.L. Smith, Ph.D.: "Plasma-Laser Interactions with Solid Polystyrene Microspheres".
8. May 1978, L.B. Gordon, M.S.E.E.: "A High Density Plasma Source".
9. May 1979, E.Y. Chu, Ph.D.: "Beat Heating in Plasmas Using CO_2 Lasers".
10. August 1980, R.L. Druce, Ph.D.: "An Experimental and Numerical Investigation of Laser-Plasma Interactions".

PUBLICATIONS
by Faculty and Staff with
Support from Grant
AFOSR-74-2639 and AFOSR-79-0034

Publications:

1. G.M. Molen, M. Kristiansen, M.O. Hagler, and R.D. Bengtson, "CO_2 Laser Heating of a Magnetized Plasma Column," Appl. Phys. Lett. 24 583 (1974).

2. W.C. Nunnally, M. Kristiansen, and M.O. Hagler, "Simple, Multiple Arc, Dielectric Switch Applied to a Theta Pinch," Review of Scientific Instruments 45, 1361 (1974).

3. M. Kristiansen and G.M. Molen, "CO_2 Laser Interaction with Magnetized Plasma," (invited paper, Proc. IEEE Region IV Conf., April 1974).

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5. W.C. Nunnally, M. Kristiansen, and M.O. Hagler, "Differential Measurement of Fast Energy Discharge Capacitor Inductance and Resistance," IEEE Trans. on Instrumentation and Measurement, IM-24, 112 (1975).

6. W.C. Nunnally, M. Kristiansen, and M.O. Hagler, "Plasma-Solid Interaction in a Theta Pinch," Appl. Phys. Lett. 26, 494 (1975).

7. D.L. Smith and W.C. Nunnally, "Electromagnetic Leaks Pin-pointed and Measured," Laser Focus Magazine, March 1975, p. 55.

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11. R.E. Dollinger and D.L. Smith, "A Novel High Voltage Probe," Proc. First IEEE Pulsed Power Conf., Lubbock, Texas, Nov. 9-11, 1976.

12. R.E. Dollinger and D.L. Smith, "An Analysis of Co-Axial Pulse Transformers," Proc. First IEEE Pulsed Power Conf., Lubbock, Texas Nov. 9-11, 1976.

INTERACTIONS

1) Papers Presented

1. W.C. Nunnally, M. Kristiansen, and M.O. Hagler, "Simple Solid Dielectric, Start Switch," International Conference on Energy Storage, Compression, and Switching, Torino, Italy, Nov. 5-7, 1974.

2. G.M. Molen and M. Kristiansen, "Carbon Dioxide Laser Interaction with Magnetized Plasma," Australian Institute of Nuclear Science and Engineering Plasma Physics Conf., Sydney, Australia, February 10-11, 1975.

3. M. Kristiansen, "Pulsed Power Technology," Air Force Sigma Xi Chapter, Washington, D.C., April, 1975.

4. W.C. Nunnally, M. Kristiansen, and M.O. Hagler, "Plasma-Solid Laser Interaction in a Theta Pinch," IEEE International Plasma Sciences Conference, Ann Arbor, Michigan, May 14-16, 1975.

5. G.M. Molen, "Multiple Channel Laser Interferometer," IEEE International Plasma Sciences Conference, Ann Arbor, Michigan, May 14-16, 1975.

6. M. Kristiansen, "CO_2 Laser Heating of Magnetized Plasmas," Univ. Stuttgart,FRG, July 24, 1975.

7. M. Kristiansen, series of 3 lectures, entitled:
   "CO_2 Heating of Magnetized Plasmas"
   "Laser and Electron Beam Heating of Plasmas"
   "Plasma Research Studies at Texas Tech University"
   Max Planck Institut für Plasmaphysik, Garching near München, FRG, during period July 6 - August 16, 1975.

8. M. Kristiansen, "CO_2 Laser Heating of Magnetized Plasmas," University of Oslo, Oslo, Norway, Sept. 24, 1976.

9. M. Kristiansen, "New Developments in Plasma Heating," Royal Institute of Technology, Stockholm, Sweden, Sept. 27, 1976.

10. R.E. Dollinger and D.L. Smith, "A Novel High Voltage Probe," First IEEE Pulsed Power Conf., Lubbock, Texas, Nov. 9-11, 1976.

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12. R. Druce, M. Kristiansen, and M.O. Hagler, "A Numerical Parameter Study of Laser Plasma Interaction," APS Plasma Physics Div. Meeting, San Francisco, CA, Nov. 14-20, 1976.

13. R. Druce, M. Kristiansen, and M.O. Hagler, "A Numerical Analysis of High Power Laser Propagation in Magnetized Plasmas," Recent Advances in Plasma Physics, Indian Academy of Sciences, Nov. 29 - Dec. 11, 1976.

14. D.L. Smith, M. Kristiansen, and M.O. Hagler, "Ablation Rates of Polystyrene Microspheres in a Theta Pinch Plasma," J. Appl. Physics 46, 11 (1977).

15. E.Y. Chu, R. Druce, L. Gordon, J. Jasper, M. Kristiansen and M.O. Hagler, "An Experimental Arrangement for Laser Beat Heating of Plasmas," Proc. of the Seventh Symposium on Engineering Problems of Fusion Research, Knoxville, Tenn., Oct. 25-28, 1977.

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19. R.E. Dollinger and D.L. Smith, "Shielded, High-Voltage Probes," IEEE Transactions on Electron Devices, Vol. ED.-26, 1553, 1979.

13. M. Kristiansen, Series of 2 lectures on "CO_2 Laser Heating of Magnetized Plasmas," U.S. - India Workshop on Plasma Physics, Ahmedabad, India, Nov. 29 - Dec. 10, 1976.

14. D.L. Smith, M. Kristiansen, and M.O. Hagler, "Ablation Rates of Spherical Polystyrene Pellets in a Theta Pinch," IEEE International Conference on Plasma Science, Troy, New York, May 23-25, 1977.

15. M. Kristiansen, "CO_2 Laser Heating of Magnetized Plasmas," Polish Academy of Sciences, Warsaw, Poland, October 1, 1977.

16. E.Y. Chu, R. Druce, L. Gordon, J. Jasper, M. Kristiansen and M.O. Hagler, "An Experimental Arrangement for Laser Beat Heating of Plasmas," 7th Symposium on Engineering Problems of Fusion Research, Knoxville, Tenn., Oct. 25-28, 1977.

17. R. Druce, M.O. Hagler and M. Kristiansen, "Experimental and Theoretical Investigations of High Power Laser Beam Propagation in Magnetoplasmas," IEEE International Conference on Plasma Science, Madison, Wisconsin, May 19-21, 1980.

2) Consulting and Advisory Functions

1. Dr. Kristiansen served as a consultant to Aerospace Corp., El Segundo, California during the period 1974-1976. He worked on pulsed power and plasma physics problems related to the dense plasma focus. Principal contact: Dr. G.M. Molen (now at Old Dominion University).

2. Dr. Kristiansen worked as a consultant to Palisades Institute in 1976-77. He worked on a pulsed power research assessment (DARPA Contract MDA903-76-C-0253). Principal contact: Warren Kramer. The resulting report was classified SECRET.

3. Dr. Kristiansen was a member of the AFWL Pulsed Power Review Panel in 1974-75. The principal AF contacts were Dr's. D. Wunsch and A. Guenther.

4. Dr. Kristiansen was a member of the National Academy of Sciences Air Force Study Board on Pulsed Power in 1977 at the AFWL. The final briefing on the study was given by Drs. Beckner (Sandia Labs) and Dr. Kristiansen to Generals Allen, Stafford, and Hendricks at Edwards AFB on Nov. 18, 1977. The final report on the project has been issued by the NRC and partly been classified SECRET.

5. Dr. Kristiansen was a member of a DOD Study Group which assessed the European State-or-the-art in pulsed power during the Summer of 1978. Principal DOD participants: A. Guenther, AFWL; R. Verga, AFAPL, F. Rose, NSWC. The final report of this study is being completed.

6. Dr. Kristiansen has been intimately involved with the organization of several DOD sponsored conferences, including:
   The First IEEE International Pulsed Power Conference, (1976)
   The Second IEEE International Pulsed Power Conference, (1979)
   The 13th Modulator Symposium, (1978)
   The 1976 NSWC Pulsed Power Systems Workshop, and
   The 14th Pulsed Power and Modulator Symposium (1980)

7. Dr. Kristiansen is organizing a pulsed power lecture series for the USAF with support from AFWL, AFOSR, and AFAPL.

8. Dr. Kristiansen has also worked as a consultant on pulsed power and plasma physics problems to LASL from 1974 to the present time.

Final Report
on
Dense Plasma Heating and Radiation Generation

AF Grant AFOSR 74-2639
AFOSR 79-0034

1. Introduction

The generation of X-rays from dense, high-energy plasmas produced by high-power pulsed sources has stimulated considerable interest because of the large number of possible applications, including diagnostic techniques, simulation of weapons effects, and even the possibility of X-ray lasers. It is relatively difficult, however, to produce a plasma that is hot enough to produce X-rays. In most cases, a relatively cool plasma must be heated by auxiliary means to obtain high energies. The AFOSR grants that supported this research was concerned with this plasma heating. The activities conducted under this grant consisted of several parts:

1. experimental and theoretical investigations of CO_2 laser heating of a dense ($n \sim 10^{23}\ m^{-3}$), preformed plasmas.
2. nonlinear optical mixing of 9.56 and 10.28 μm laser radiation in a plasma
3. investigations of solid-laser-plasma interactions
4. a study of pulsed power systems and technology

2. Laser Heating of Dense Plasmas

The experimental portion of the laser-plasma interaction investigation used a large CO_2 laser obtained from AFWL and a linear discharge plasma source designed and constructed at

Texas Tech especially for the laser-plasma interaction experiment and the nonlinear optical mixing experiment. The experimental arrangement is shown in Fig. 1. Two plasma column lengths were used for the laser-plasma interaction experiment, 0.4 m and 0.13 m. The initial plasma density was varied from 5×10^{22} m^{-3} to 3×10^{23} m^{-3} by adjusting the filling pressure. The initial temperature ranged from 1.8 eV to 2.2 eV, depending on the filling pressure. The plasma was confined by a 2.9 T axial magnetic field. The laser produced a 35 ns FWHM pulse with a total of 30 J incident upon the plasma. Since confocal unstable resonator optics were used, the laser beam was annular with an o.d. of 0.102 m and an i.d. of 0.051 m at the laser output. The principal diagnostics were interferometry for density and spectroscopy for temperature. The working gas was hydrogen in all cases.

The theoretical portion of this investigation consisted of a 2 1/2 dimensional computer code developed at Texas Tech to simulate the interaction of a CO_2 laser with an underdense, preformed, fully ionized, cylindrical, hydrogen plasma. Mechanisms included in the code are:

1. inverse bremsstrahlung heating of electrons
2. electron-ion equipartition of energy
3. thermal conduction in electrons and ions
4. fluid solutions to plasma dynamics
5. laser refraction by the plasma.

The code self-consistently solves for the plasma density and temperature and the laser intensity distributions. Provision

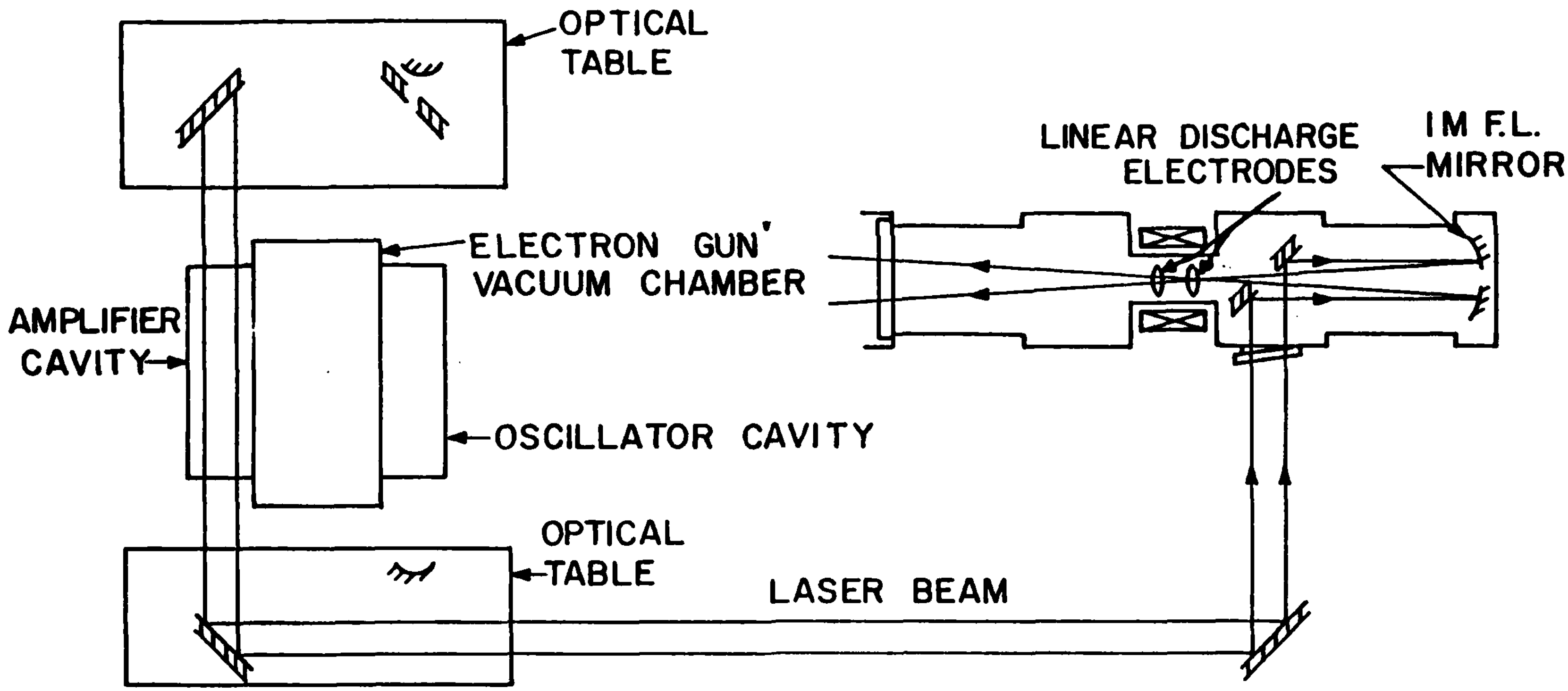


Fig. 1 Schematic of Experimental Apparatus

is made in the code for either collimated or focused laser beams. The plasma may be magnetically confined but not necessarily so. The initial densities, velocities, and temperatures of electrons and ions are input as smooth functions of r and z. Azimuthal symmetry is assumed throughout. Plasma radiation is not considered since the code is designed to simulate relatively cool plasmas.

The experiment was conducted and simulated for several cases. The results for the 2 Torr, 0.13 m plasma column will be presented, in part, here. The peak laser intensity at the laser beam with the end of the plasma was 4.1 x 10^9 W/cm^2 with a beam o.d. of 0.0064 m. The initial density profile is shown in Fig. 2. The desired density minimum on axis is clearly obtained. The initial temperature for this case is 2.2 eV. A parametric plot in z of the electron temperature at peak laser intensity is shown in Fig. 3, while a comparison of the calculated and observed radial electron temperature profiles at z = 0.065 m is shown for the peak electron temperature in Fig. 4. Figure 5 shows a parametric plot in z of the density perturbation 40 ns after the end of the laser pulse, while Fig. 6 shows a comparison of calculated and observed radial fringe perturbation at z = 0.065 m at the same time. Agreement between calculated and observed temperature profiles is seen to be good (which also indicates that the ray tracing is accurate). The density perturbation, on the other hand, does not agree well in magnitude. This disagreement probably indicates that the pressure term in the fluid model of the plasma needs improvement.

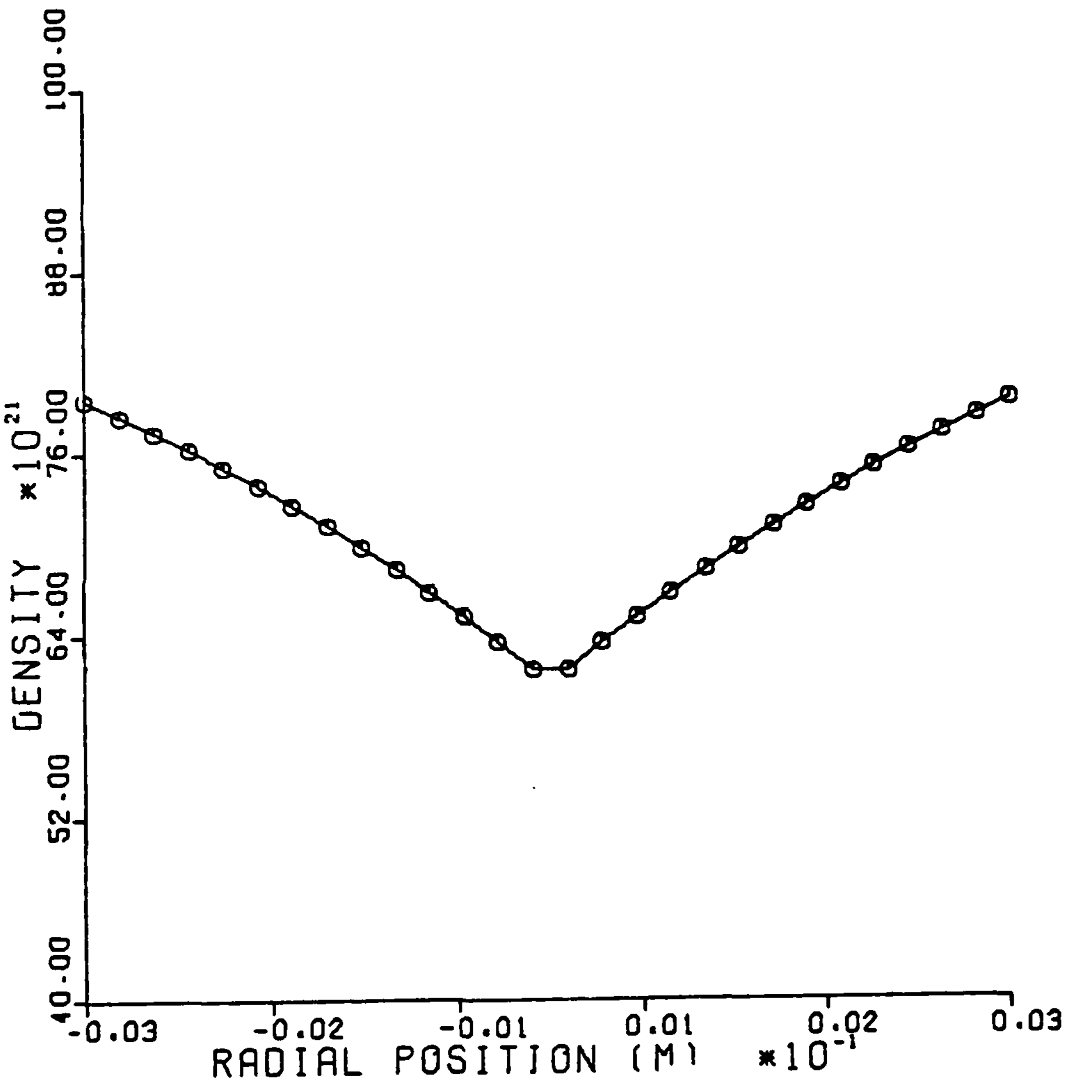


Fig. 2 Initial Density at 2 Torr Filling Pressure
for 0.13 m column

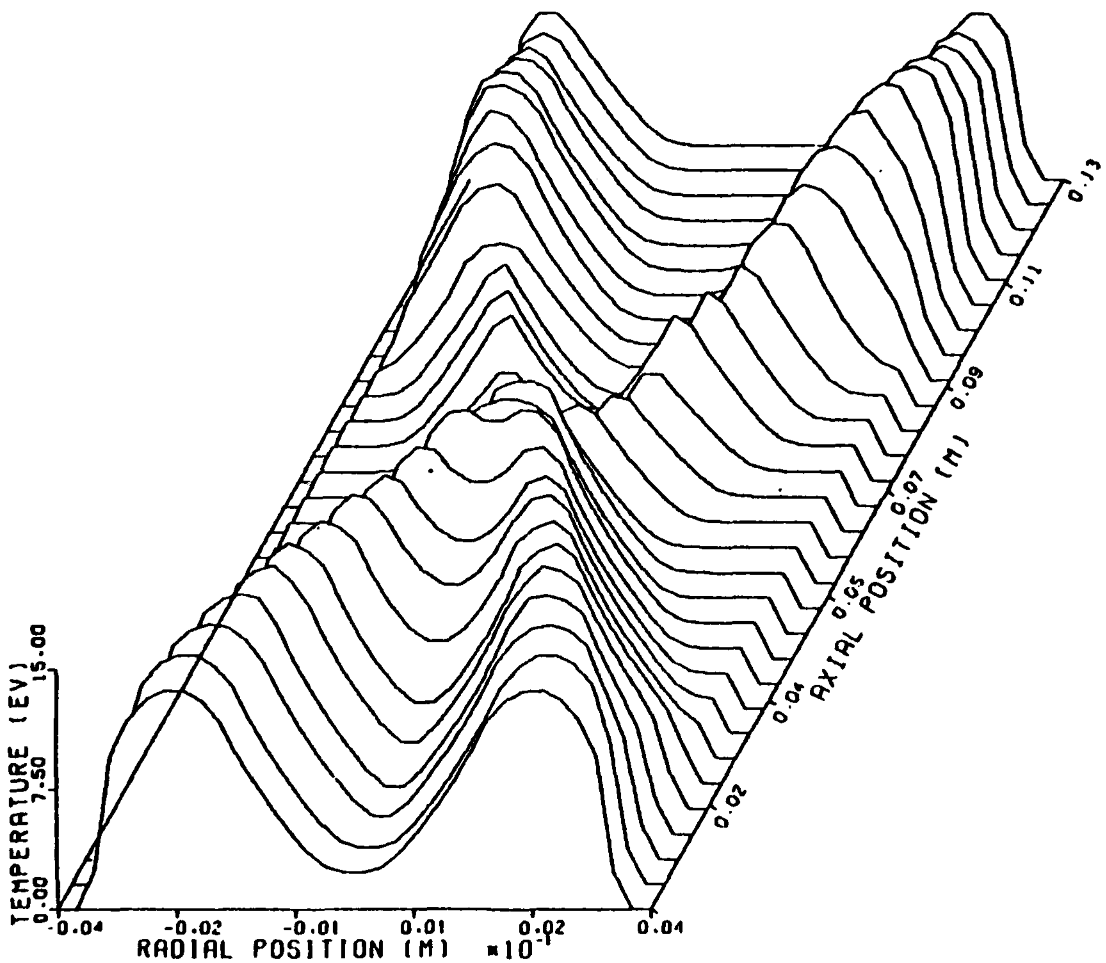


Fig. 3 Calculated Electron Temperature 30 ns After Laser Initiation in Two Dimensions for the 2 Torr, .13 m Column

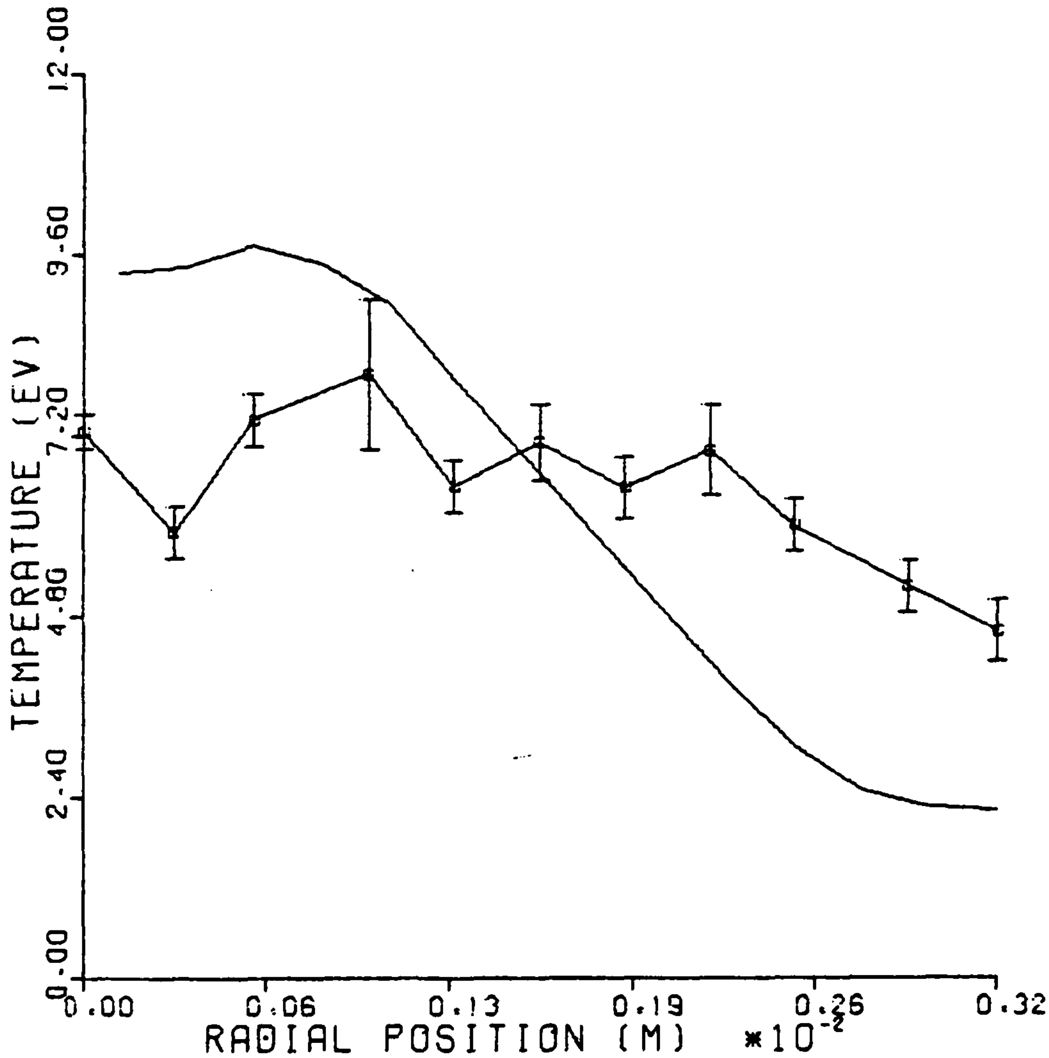


Fig. 4 Comparison of Calculated and Observed Peak Electron Temperatures for the 2 Torr, 0.13 m Long Plasma Column

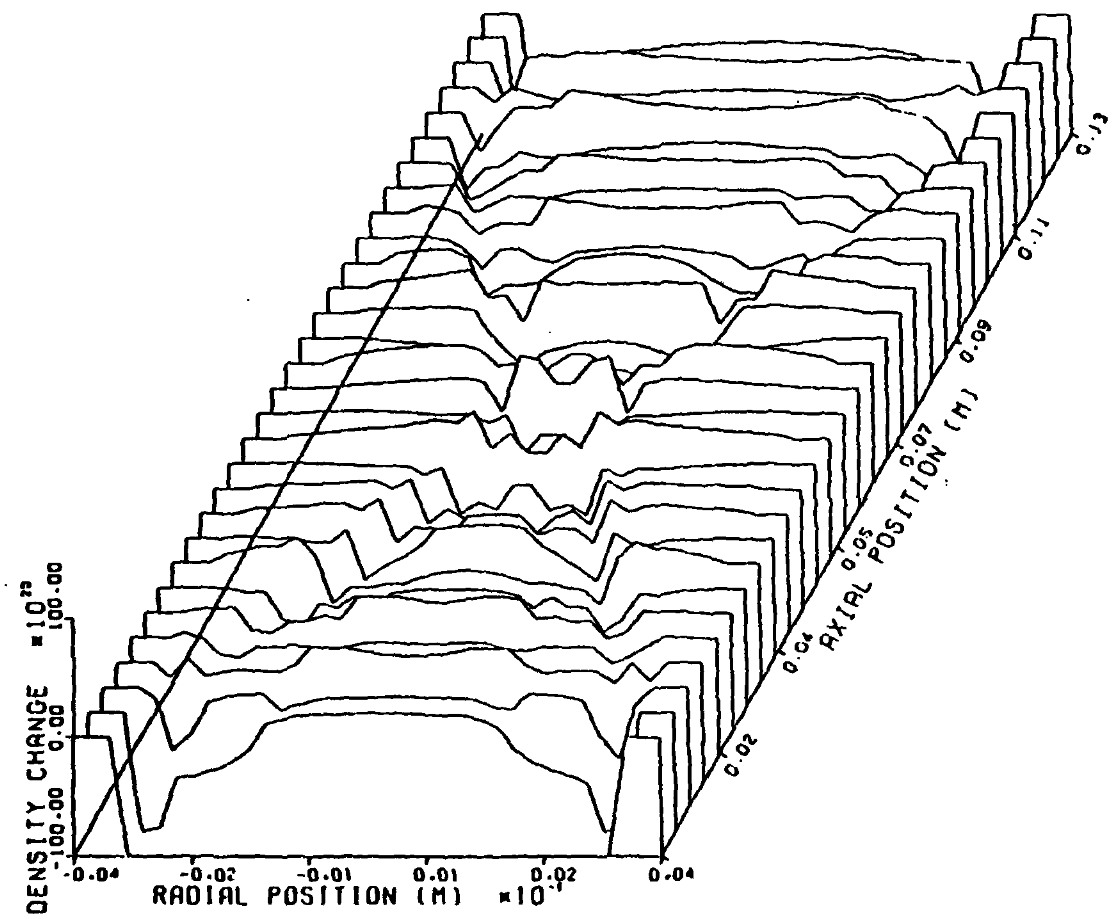


Fig. 5 Calculated Final Density Perturbation 40 ns After Laser Pulse in Two Dimensions for the 2 Torr, .13 m Column

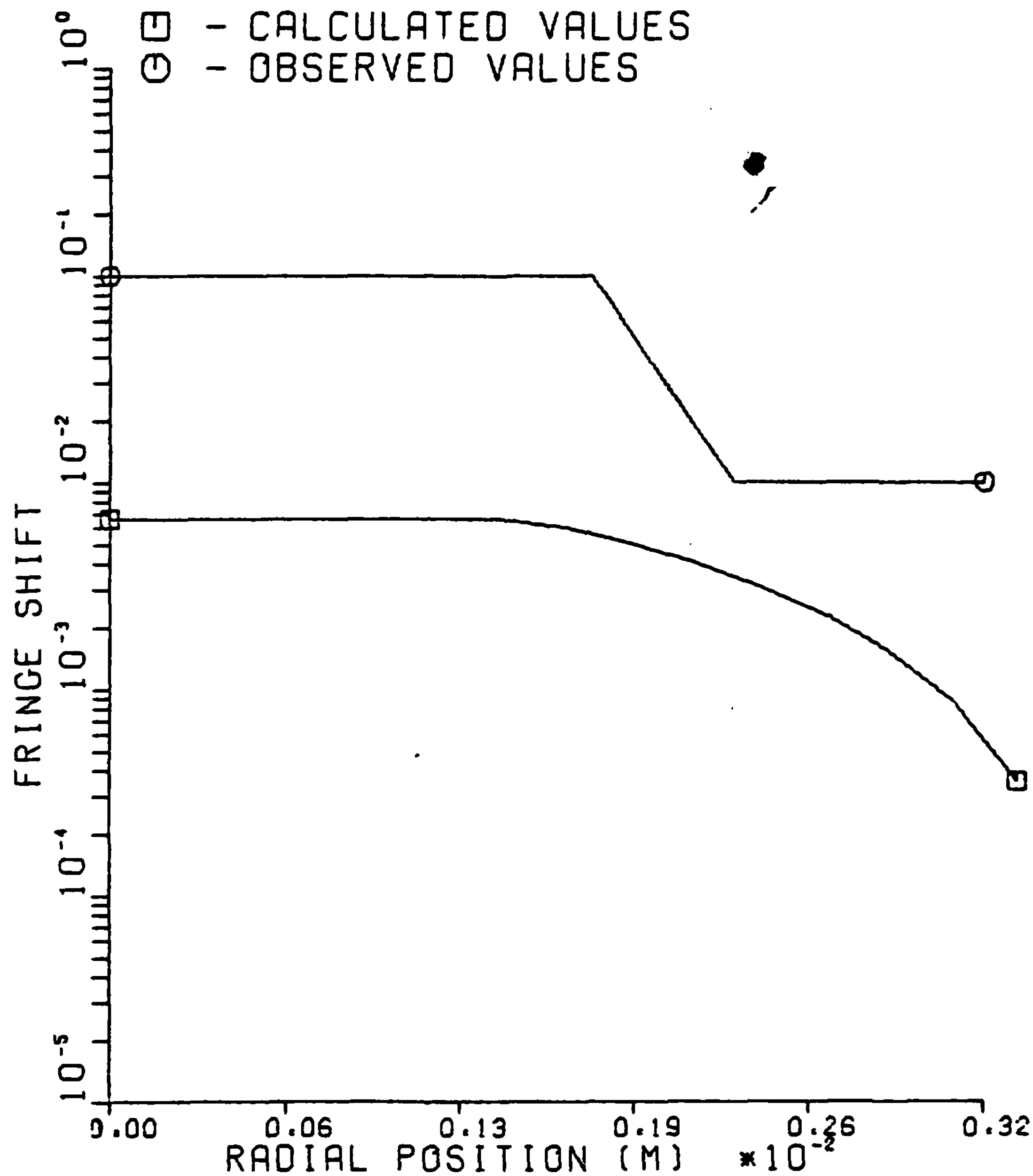


Fig. 6 Comparison of Calculated and Observed Fringe Perturbation at z = 0.0675 m for the 2 Torr, 0.13 m Long Plasma Column

3. Nonlinear Optical Mixing

The nonlinear optical mixing investigation was primarily an experimental effort designed to test the validity of the theory that two laser beams of different frequency may interact in a nonlinear manner to excite a large amplitude plasma wave (beat heating). Consider two laser beams with frequencies ω_o, ω_1 and propagation vectors $\bar{k}_o$, $\bar{k}_1$, together with a small amplitude electron density fluctuation. The electrons will respond to the incident electric fields with a quivering velocity of

$$V = (eE_o/m\omega_o)\cos(\omega_o t + \bar{k}_o \cdot \bar{z} + \phi_o)$$
$$+ (eE_1/m\omega_1)\cos(\omega_1 t + \bar{k}_1 \cdot \bar{z} + \phi_1)$$

where E_o, E_1 are the incident electric fields. However, due to the associated magnetic fields in the perpendicular direction, the electrons will experience Lorentz forces in the longitudinal direction with magnitudes proportional to vB or EB. The product of various cosine terms gives rise to terms such as $\cos(\omega_o t + 2\bar{k}_o \cdot \bar{z})$, $\cos(2\omega_1 t + 2\,\bar{k}_1 \cdot \bar{z})$, $\cos\,((\omega_o + \omega_1) + (\bar{k}_o + \bar{k}_1)\cdot\bar{z})$, and $\cos((\omega_o \cdot \omega_1)\, t + (\bar{k}_o \cdot \bar{k}_1)\cdot\bar{z})$. Each of these terms drives the electrons to oscillate at its corresponding frequency. In general, the amplitude of these forced oscillations will be small. However, if $\omega_o - \omega_1 = \omega_2$, $\bar{k}_o - \bar{k}_1 = \bar{k}_2$, the wave number of the local density fluctuation, and ω_2 and $\bar{k}_2$ obey the Bohm-Gross dispersion relationship

$$\omega_2{}^2 = \omega_{pe}{}^2 + 3\,Ve^2\,k_2{}^2$$

then the fluctuations will be enhanced with the maximum energy

transfer efficiency limited by the Manley-Rowe limit which is $\hbar\omega_2/\hbar\omega_o = \omega_2/\omega_o$. The electron plasma waves thus excited may be damped (Landau damping or collisional damping are two possible mechanisms) to heat the plasma. In addition, theory predicts that this heating will be relatively unaffected by increasing plasma temperature [2] (as opposed to inverse bremsstrahlung heating which shows a $1/T_e^{3/2}$ dependence). Beat heating will not occur below a certain intensity threshold, however.

The experimental arrangement for the nonlinear mixing experiment was very similar to the setup for the laser-plasma interaction experiment with the addition of an absorption cell to the CO_2 laser and an additional 0.5 m focusing mirror added to the plasma source. The absorption cell allows the introduction of a selective absorption medium (SF_6) into the beam path to serve as a laser line selector. With over 25 Torr of SF_6, the laser oscillated exclusively at 9.56 μm. Lowering the pressure to 12.5 Torr allowed lasing simultaneously at 10.28 and 9.56 μm to give a beat frequence $\omega = 1.38 \times 10^{13}$ sec $^{-1}$, which corresponds to a critical plasma density of 5.9×10^{16} cm^{-3}. The 1.5 m focusing mirror allowed the two-frequency laser beam to be passed through the plasma simultaneously in both directions to allow the possibility of both parallel ($\bar{k}$ vectors parallel) and anti-parallel ($\bar{k}$ vectors in opposite directions) beat heating. This mirror was important because it allowed for anti-parallel beat heating (which should be much more efficient than parallel heating) without

requiring the extremely difficult task of synchronizing two lasers with nanosecond accuracy.

The results obtained from the mixing experiment are informative. Since the "resonant" density for the mixing experiment is at the lower end of the range used for the laser-plasma interaction experiment, the filling pressure was varied from 1.0 to 1.9 Torr for the mixing experiment. Table 1 shows the initial on-axis electron density corresponding to the range of filling pressures from 1.0 to 1.9 Torr (this experiment also displayed a density minimum on-axis). Table 2, on the other hand, is the initial electron temperature for the same range of filling pressures. The working gas used for this investigation was helium because helium has a higher atomic mass number than hydrogen with a correspondingly longer end loss time and because it allows satellite lines to be used as a diagnostic. The peak laser powers are commensurate with those found in the laser-plasma interaction experiment. The plasma column length is 0.1 m with the vacuum focal spot at the axial and radial center of the column ($r = 0$, $z = 0.05$). The vacuum focal spot had a diameter of 0.0025 m.

Table 3 shows a comparison of the single frequency (inverse bremsstrahlung) heating and double frequency heating (beat heating). If inverse bremsstrahlung heating were the only mechanism operating, the heating for the two frequency beam would be expected to produce less heating in all cases (due to the fact that the total laser energy is less and that part of the energy is at a shorter wavelength). However, this

Filling Pressure (Torr)	Electron Density ($\times 10^{22}$ m^{-3})
1.0	3.9 $\pm$ .45
1.1	4.2 $\pm$ .45
1.2	4.6 $\pm$ .45
1.3	4.8 $\pm$ .45
1.4	5.0 $\pm$ .45
1.5	5.3 $\pm$ .45
1.6	5.7 $\pm$ .45
1.7	5.8 $\pm$ .45
1.8	6.2 $\pm$ .45
1.9	6.5 $\pm$ .45

Table 1 On-Axis Average Plasma Densities at $t = 5$ μs for Various Filling Pressures.

Filling Pressure (Torr)	Temperature (eV)
1.0	4.46 ± .22
1.1	4.44 ± .22
1.2	4.37 ± .22
1.3	4.28 ± .21
1.4	4.23 ± .21
1.5	4.24 ± .21
1.6	4.33 ± .22
1.7	4.15 ± .21
1.8	4.19 ± .21
1.9	4.20 ± .21

Table 2 On-Axis Average Plasma Temperatures at $t = 5\ \mu s$ for Various Filling Pressures

Filling Pressure (Torr)	Single Frequency Laser Heating (eV)	Double Frequency Laser Heating (eV)
1.0	27.8 ± 10.3	23.1 ± 9.3
1.1	38.5 ± 12.7	30.0 ± 12.3
1.2	52.6 ± 15.5	35.1 ± 12.3
1.3	53.2 ± 21.1	47.7 ± 16.5
1.4	90.7 ± 26.9	38.4 ± 18.5
1.5	42.8 ± 17.6	44.4 ± 16.7
1.6	67.8 ± 18.3	38.6 ± 15.0
1.7	104.9 ± 28.8	59.1 ± 19.0
1.8	77.6 ± 23.5	49.9 ± 21.3
1.9	79.3 ± 29.6	66.9 ± 27.1

Table 3 Single and Double Frequency Laser Heating Results Measured Using Diamagnetic Loop Method

is seen not to be the case at 1.5 Torr. On applying the paired t-test to the data, the observed departure is significantly different from the rest of the measurements with a better than 99% confidence level. These results suggest that there is heating which is not accounted for by inverse bremsstrahlung absorption at 1.5 Torr (an initial density of 5.3 x 10^{22} m^{-3}), an indication that beat heating is present at this pressure. It does appear, however, that this additional heating is not as strong as expected. This weak heating is probably due to detuning of the interaction after very short times. To understand these results, one notes that at 4.5 eV, the plasma damping rate, as a result of electron collisions, is approximately 3.6 x 10^{-2} ω_{pe} with insignificant contributions from Landau damping. At 40 eV, for example, the damping rate is 1.36 x 10^{-2} ω_{pe} and 2.05 x 10^{-3} ω_{pe} from collisional damping and Landau damping, respectively. Therefore, for the plasmas encountered in this investigation the $\nu c/\omega_{pe}$ ratio will be at most on the order of 1%.

If one assumes a density scale length of 0.1 L at the center of the plasma column, where L is the length of the plasma column, an optical mixing interaction zone on the order of 0.01 m results [3]. Using a laser power density of 10^{10} W/cm^2, one finds that a large relative action transfer (~1) is to be expected. With weak damping ($\nu_c/\omega_{pe} \lesssim 0.01$) and a large relative action transfer, one then expects a large amplitude plasma wave which leads to electron trapping and consequently energetic electron production. The hot electrons produced

will have a velocity approximately equal to the phase velocity of the plasma wave, which is about 0.036 c, where c is the speed of light in vacuum. The time required for those hot electrons to escape from the resonance zone will be less than 1 ns with each electron carrying an energy of about 330 eV. However, if one assumes that all of the energy in the plasma wave is converted into kinetic energy of the hot electrons and with a beat heating efficiency of 7% (shown to be a reasonable number by Chu [2]), the number of hot electrons generated in 1 ns will be 6.5×10^{14}. This number, when compared to the 2.95×10^{15} particles in the 0.01 m long, 2.5 mm diameter interaction volume, gives a 22% change in the density as the hot electrons produced stream out of the interaction volume. Because of weak damping ($\nu_c/\omega_{pe} \leq 1\%$) a change of less than 1% in the plasma frequency will detune the optical mixing process from resonance. One, therefore, expects the optical mixing process to stop long before the 22% density change occurs.

4. Solid-Laser-Plasma Interactions

Like the investigation of nonlinear optical mixing, the solid-laser-plasma interaction investigation was primarily experimental [4]. The solid -laser-plasma interaction, of course, consists of three related interactions, the solid with the plasma, the solid with the laser, and the laser with the plasma. The laser plasma interaction part of this experiment is very similar to that described previously for the laser-plasma interaction investigation and will not be repeated here.

When a pellet is exposed to a hot, dense plasma, its surface rapidly heats up and molecules are vaporized by electron bombardment. As soon as the ablation cloud forms, it begins shielding the pellet from the incident plasma electron energy flux due to elastic and inelastic collisions. In general, the presence of a background gas, the reflectivity of the target surface, the surface quality and finish, the laser wavelength and the pulse duration are all important parameters that modify the process and must be specified for a given experiment. The laser energy absorption process depends on whether the irridiated solid is transparent, reflective, or absorptive. If it is transparent, absorption occurs at the lattice irregularities or impurities at or inside the surface, and the situation is quite similar to gas breakdown. For metallic targets, the initiation is more straightforward. Here the initial conductivity of a smooth surface is quite high. Radiation falling on this surface interacts with the conduction band electrons in the skin depth. These electrons then respond collectively to the field, and energy is absorbed through free-free interactions, collisions of electrons with imperfections, etc.

Recently a general model for the transonic flow of ablating pellet material, applicable to a wide class of plasma conditions, has been developed [5]. Initial assumptions inherent to this theory are a quasi steady ablation rate (the pellet regression speed, $\dot{r}_p$, is slow with respect to the time of cloud formation) and the development of a physical shock front far from the pellet surface such that it has no effect on the absorbing

portion of the primarily neutral cloud. The most important mechanism in the interaction is the energy absorption by the neutrals, which display gas dynamic motion. This mechanism almost controls the ablation rate and directly couples back to surface vaporization. Parks [5] shows that the pellet surface regression speed scales as

$$\dot{r}_p \sim n_e^{1/3}\, r_p^{-2/3}\, T_e^{1/2}\, \gamma^{-2/3}$$

where r_p is the instantaneous pellet radius and γ is an "effective energy flux cross section". Included in γ is an energy dependent loss function, L(E), which accounts for the physical properties of the gas medium. It is now possible to predict a scaling law for the lifetime of a hydrogen pellet:

$$\tau_p \sim \frac{r_{po}}{\dot{r}_p} \doteq \frac{r_{po}^{5/3}}{n_e^{1/3}\, T_e^{1.71}} \qquad (1)$$

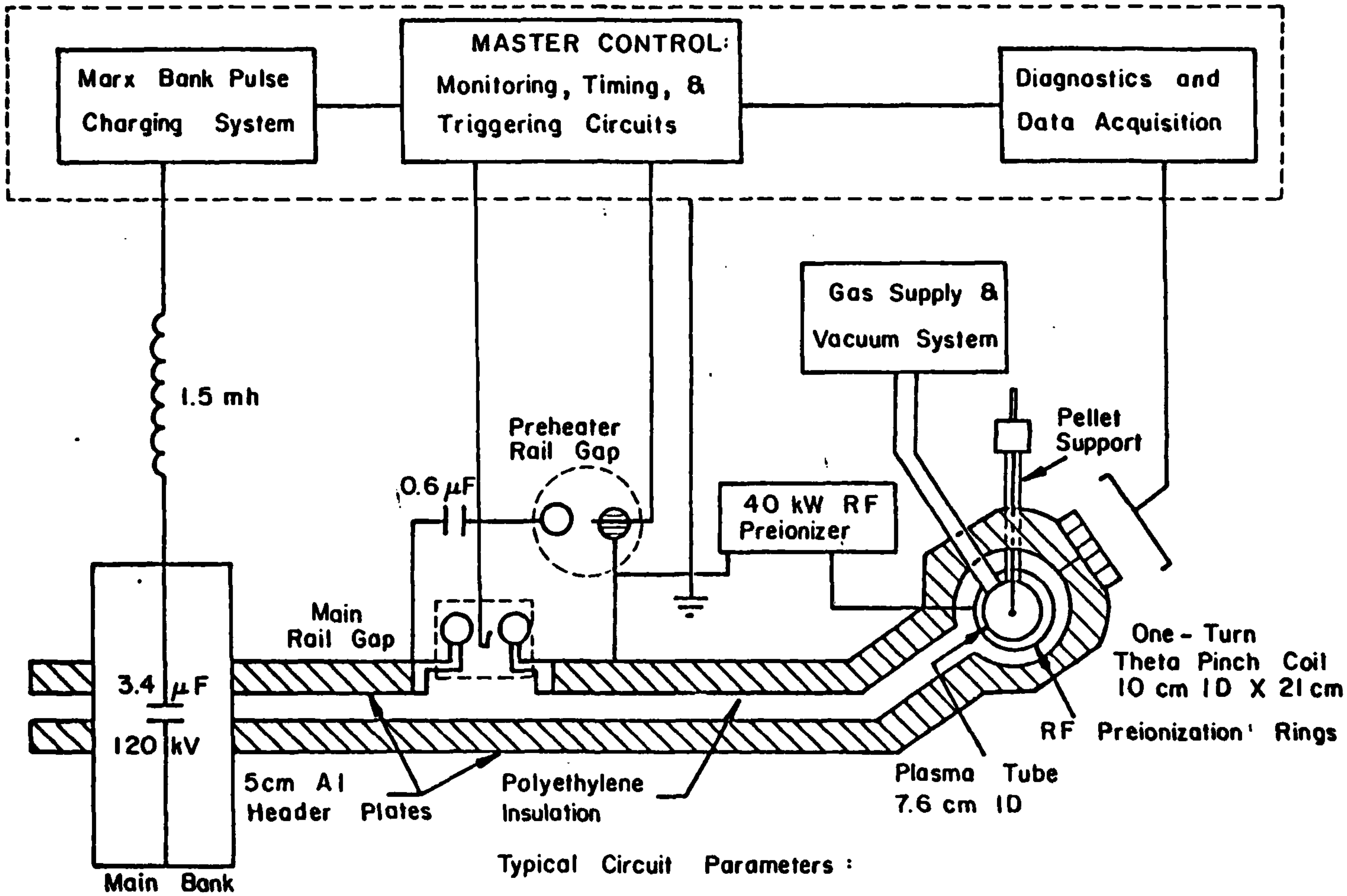
The respective individual cross sections of a polystyrene gas that contribute to L (E) are not well known. However, if it is assumed that the polystyrene cloud has the same form for L(E) as does molecular hydrogen and if $\Delta r/\Delta t$ is substituted for $\dot{r}_p$ in Eq. (1), then

$$n_e^{1/3}\, T_e^{1.71} \doteq K\, (r_{po})^{2/3}\, \Delta r_p \qquad (2)$$

where Δr_p corresponds to the measured change or reduction in pellet radius and K is a proportionality constant containing, among other things, the pellet-plasma interaction time, Δt. Thus the change in pellet radius due to the plasma can be predicted.

In order to expose a pellet to a hot, dense plasma under reproducible conditions, a well-understood plasma source and a means of accurately locating the pellet with respect to the plasma were needed. The plasma source used was a fast theta pinch shown schematically in Fig. 7. This theta pinch produced plasma densities from 2.4×10^{22} m^{-3} to 7.7×10^{22} m^{-3} and electron temperatures from 108 to 126 eV for filling pressures of 45-90 mTorr. The column length was 0.2 m with a diameter of 0.01 m. The working gas was hydrogen. The polystyrene pellets used were suspended in the plasma using fine glass threads attached to the pellet with Permabond 101 glue and were positioned at the focal spot of the ruby and CO_2 lasers (used to illuminate the pellets) using a HeNe alignment laser. The pellets had radii from 50 to 150 μm. Each pellet was measured before insertion into the plasma. The ruby laser used in the experiment was a Q-switched, Holobeam, Series 301 producing a 30 ns FWHM pulse containing an energy of approximately 2.5 J. Attempts were also made to use a 100 MW, 200 ns pulse length, CO_2 TEA laser to illuminate the pellet. By the nature of its design, however, it was inherently sensitive to the electrical noise generated by the theta pinch and would always prefire. A schematic of the optical setup is shown in Fig. 8. The principal diagnostics used were spectroscopy and interferometry.

Although it was not possible to complete all of the investigations that were desirable, sufficient information was accumulated to satisfy the major goals of the research. The basic interaction mechanisms were observed and the ablation



Typical Circuit Parameters :

Charging Voltage ~ 70 kV	Quarter Period ~ 1.2 μs
Theta Coil Inductance ~ 40 nH	Maximum Current ~ 400 kA
Total Circuit Inductance ~ 220 nH	Maximum Magnetic Field ~ 2.3 T

Fig. 7 Theta Pinch Circuit Diagram and Typical Parameters.

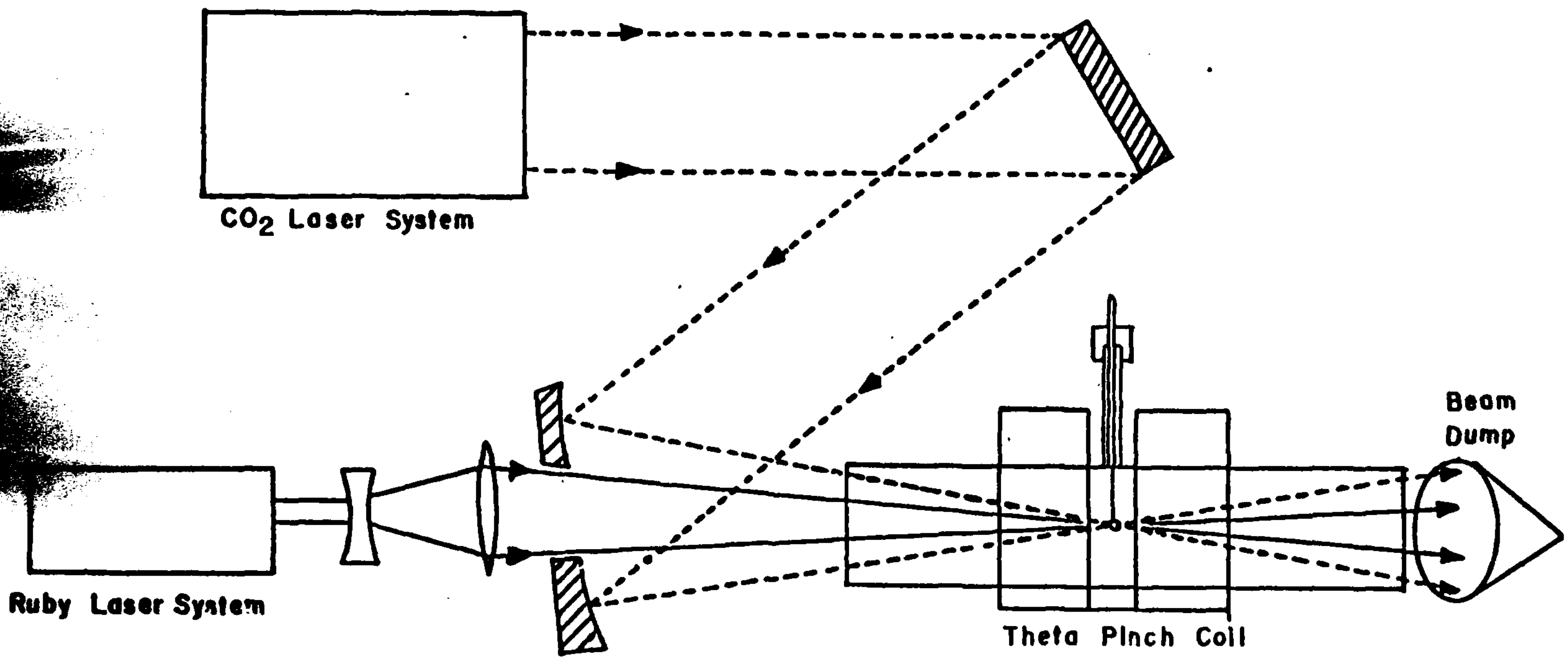


Fig. 8 Laser-Pellet-Plasma Interaction Scheme.

rates of the polystyrene spheres were directly measured and plotted as a function of various plasma parameters.

Experimental data showing a linear relationship between the left-hand-side (plasma parameters) and right-hand-side (pellet parameters) of Eq. (2) would be sufficient to show the validity of the scaling law. This possibility was investigated and the results are shown in Fig. 9. Previously collected data on the plasma parameters (without pellets) determined the four suitable filling pressures presented in the figure. Typically, r_{po} was between 50 and 150 μm while Δr_p was between 1 and 6 μm. The dashed error bars represent one standard deviation for all the collected pellet data (up to ten pellets per filling pressure). The dashed straight line was fitted to these data by a least squared technique. The large horizontal error bars are due chiefly to the errors in measuring the pellet diameters. The solid error bars represent one standard deviation for a reduced number of pellets (six per filling pressure) after applying a statistical technique known as "Chauvenet's criterion" in which observations whose deviation from the mean were greater than approximately two standard deviations were discarded completely. Again a least squares fit was used to locate the solid straight line whose slope can be used to determine the proportionality constant in Eq. (2). The average data do tend to support the scaling theory, but the error bars are still too large to draw any definite conclusions. Any further treatment of the data would be unrealistic. Accumulating many more data samples

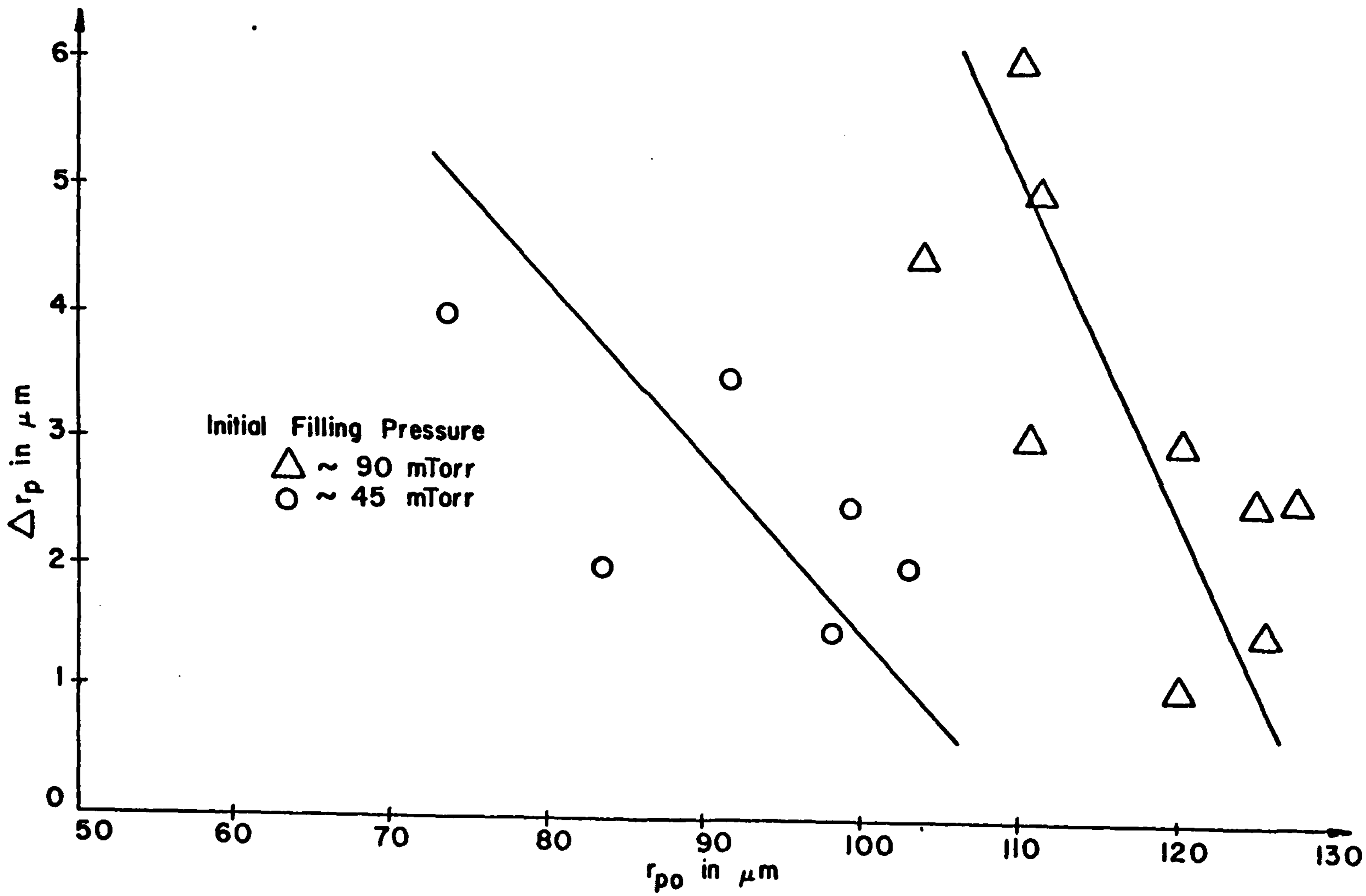


Fig. 10 Pellet Radius Reduction Versus Initial Pellet Radius.

from the experiment would have been the best way to improve the results.

Figure 10 presents some of the pellet data for two filling pressures, plotting the reduction in radius against the initial pellet radius. Since the interaction time, Δt, is assumed to be a constant 2 μs for this experiment, the vertical axis actually represents the pellet surface regression speed, $\dot{r}_p$, or indirectly, the ablation rate, given the density of a uniform polystyrene sphere($\cong$1.05 g/cm^3). The two straight lines were fitted by a least squares method and are included only to show the tendency for pellets exposed to higher initial filling pressures to change more.

By comparing the subsequent ionization stage intensities of carbon, the investigations revealed that at least the outer layers of the ablation cloud acquired temperatures between 2 and 6 eV, on time scales small with respect to the plasma-solid interaction time, depending upon the initial filling pressures and pellet sizes. No direct correlation could be made between the line intensities and pellet sizes because the small axial variation in the fixed pellet positions affected the total intensity observed through the light pipe's acceptance cone.

Figure 11 shows line drawings of three cases of the observed carbon line, CIII (569.5 nm), at one filling pressure, p_o = 60 mTorr. The plasma background, or continuum, near this wavelength is shown in part (a) of the figure. The signal initially occurs about 400 ns after triggering the rail gap

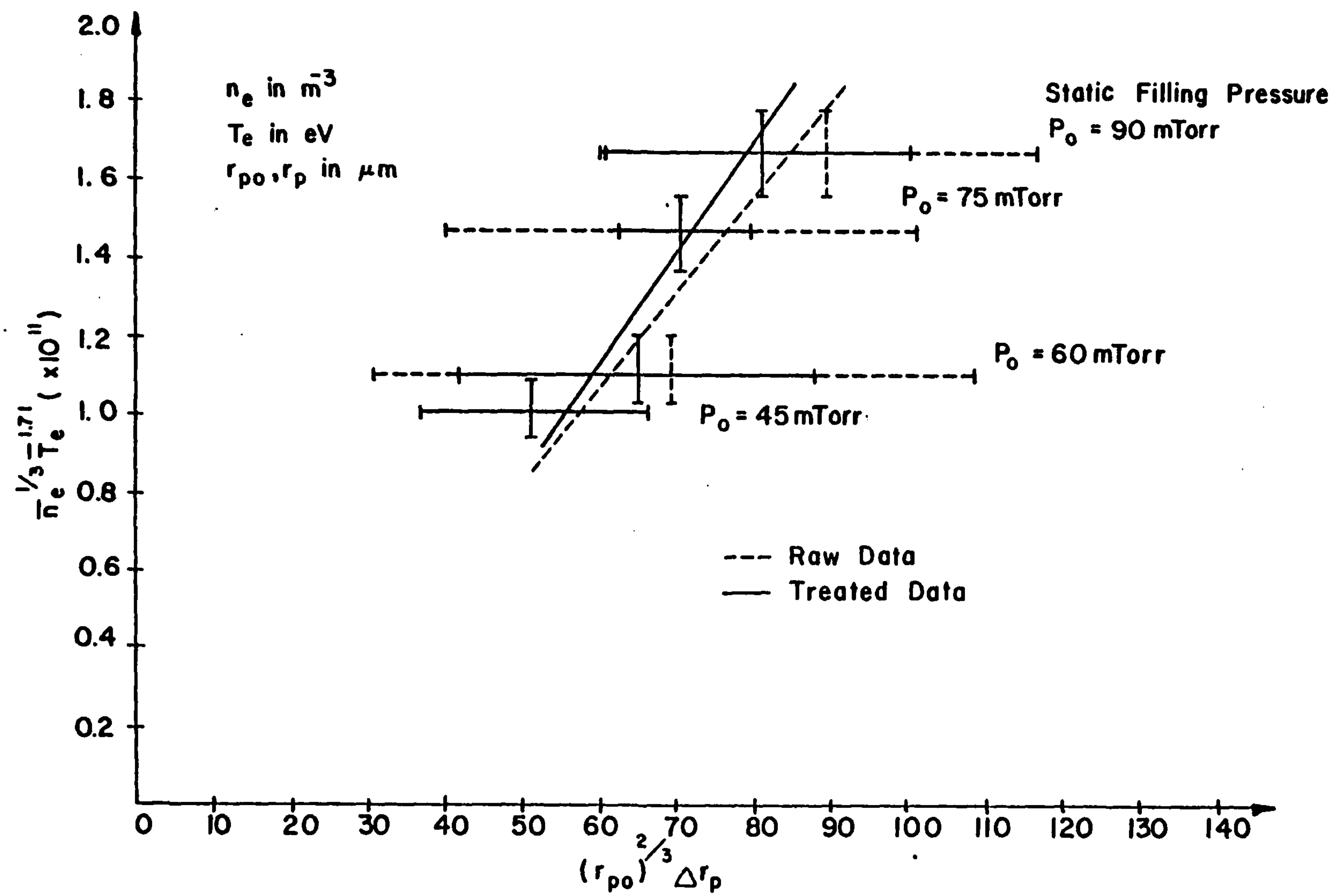


Fig. 9 Experimental Results in Terms of the Scaling Law Variables.

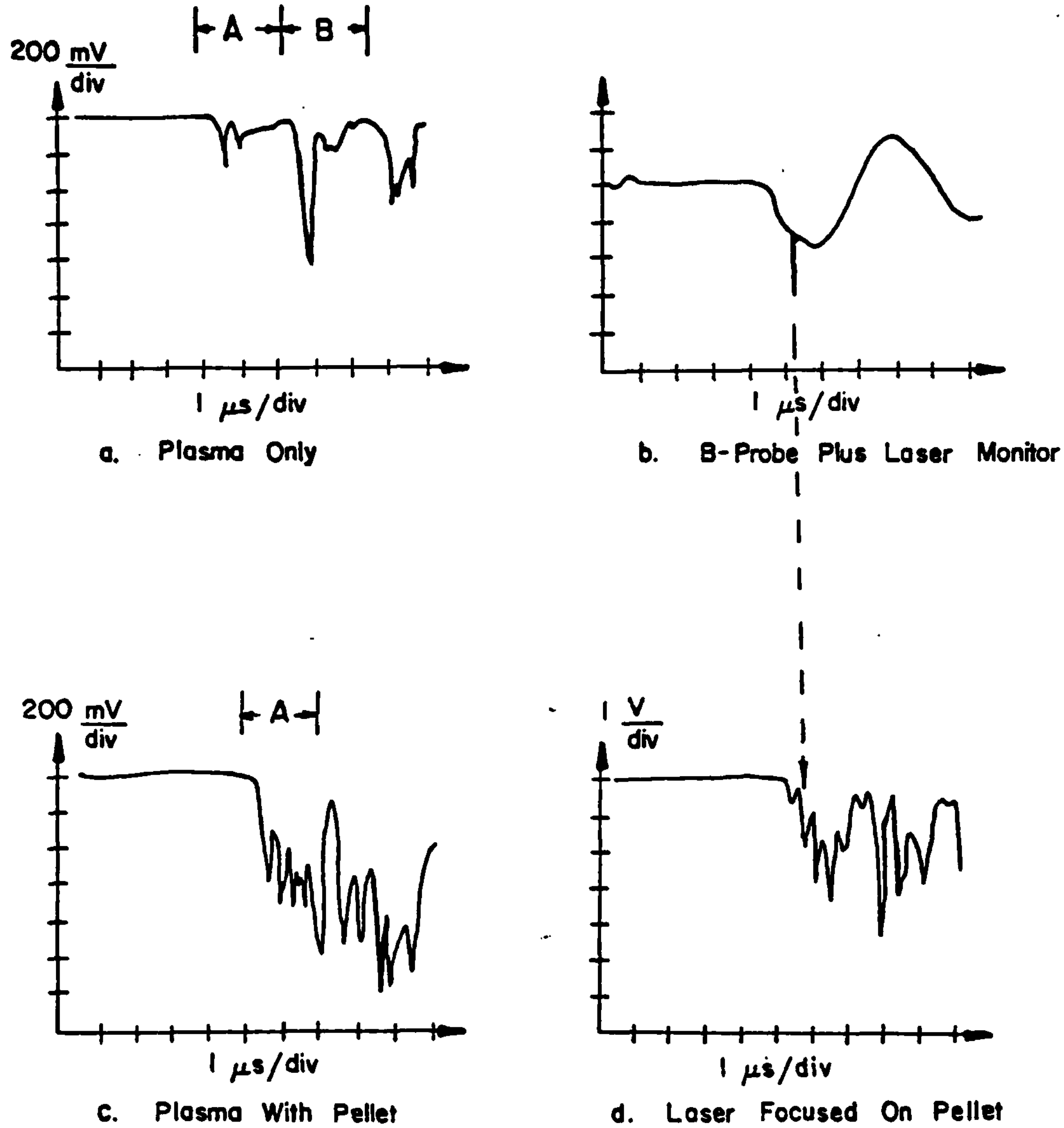
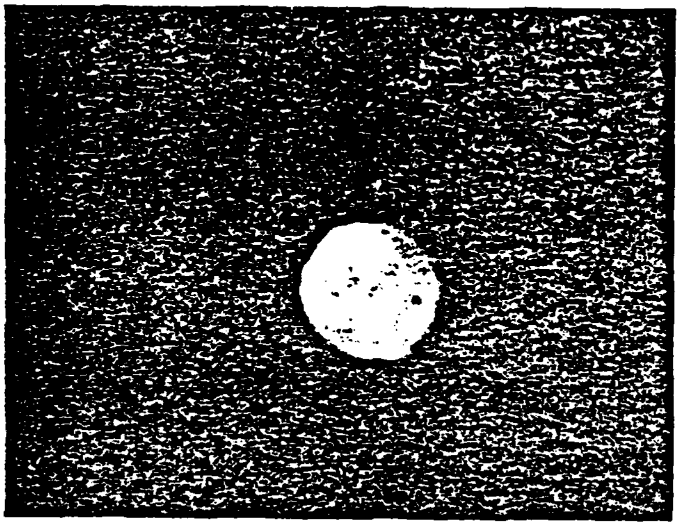


Fig. 11 CIII Line Intensities Versus Time for P_0 = 60 mTorr.

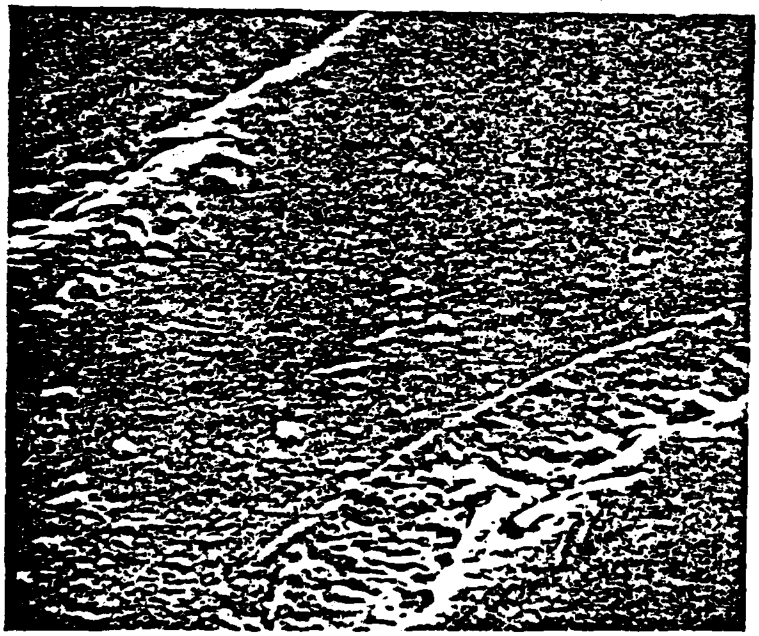
switch, and the first few negative-going peaks in region A correspond to the radial hydromagnetic oscillations (inertial bouncing) as the plasma is being shock heated ahead of the rising magnetic field. The large spike early in region B occurs at the beginning of the second half-cycle, after the magnetic field (see part (b)) has rung back through zero. As the plasma interacts with the vessel walls, carbon residue, and so forth, it becomes dirty and cold and is no longer of interest for studying the pellet-plasma interaction. Comparing part (a) with the case in which a pellet is exposed to the plasma in part (c) makes it apparent that there is considerable ionization throughout region A.

The addition of a 30 ns, 2.5 J pulse from the Q-switched ruby laser focused on the pellet cloud produced the effect shown in part (d) of Fig. 11. The laser pulse timing monitor that is added to the B-field display of part (b) shows, with a dashed line, the approximate time the laser was discharged with respect to part (d). Noting the different vertical scales of parts (c) and (d) one can see that the amplitudes of the first peaks are roughly the same, as they should be for similar experimental conditions. A considerable boost in the line intensity is evident when the laser was fired and for some time thereafter.

As indicated by the examples of Fig. 12, pellets hit by a partially focused laser (about 3 mJ delivered to one hemisphere) were pitted or burned in some asymmetric fashion, in contrast to the effect of the plasma, alone. The recovered pellets that were exposed to the plasma, alone, appeared to be slightly



(a) "Large" Crater in Pellet.



(b) A Pellet Surface Magnified 13,000x.

Fig. 12 Examples of Low Intensity Laser Exposure.

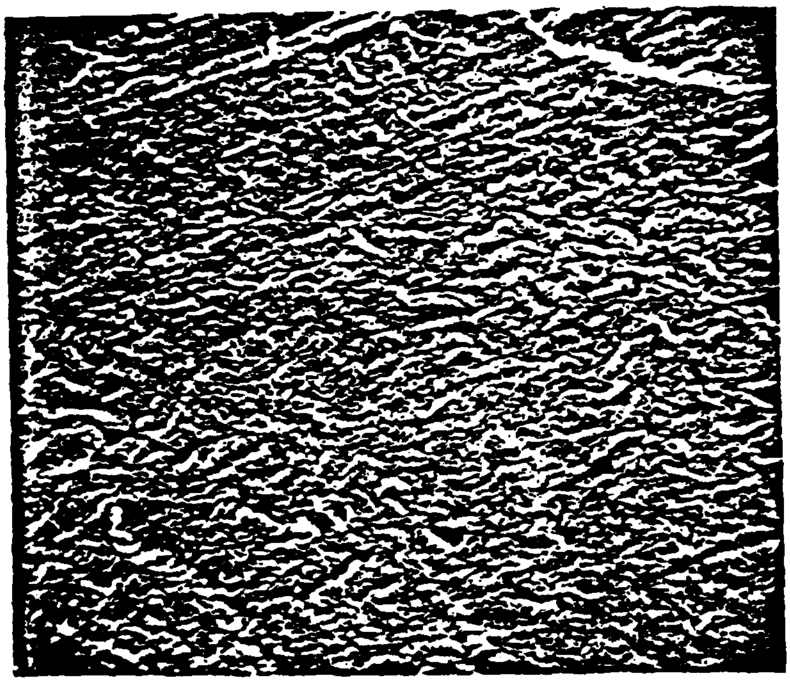
elliptical. This result might be expected from an interaction with a cylindrical plasma that is radially pinched. The difference between the major and minor diameters was usually about two microns, just within the measurement capability. Examining the surface detail under a 13,000X magnification, a scanning electron beam microscope indicated that the pellets received a fine polish from the interaction with the plasma. Fig. 13, part (a), is a photograph of a 253 μm diameter microsphere before exposure to the plasma, and part (b) represents the pellet's surface after interacting with a plasma of 60 mTorr filling pressure. The observed area is about 0.03% of the total pellet surface.

Only about 100 mJ of infrared energy from the CO_2 Tea laser could be deposited on the pellets in a vacuum. No visible or carbon line radiation was observed, which implies that little or no ionization occured. The only observable effect on the pellet according to microscope analysis was the occurrence of a cloudy or translucent appearence. Even the supporting fiber was not broken although it did appear to be deformed. Hence, an ionized pellet cloud probably should be preformed before infrared energy can be efficiently absorbed.

5. Pulsed Power Technology

It can be seen from the experimental arrangements for all of the aforementioned investigations that pulsed power concepts are utilized extensively in most plasma experiments. In addition, pulsed power techniques are also useful in such areas

(a) Typical Pellet Surface Before Plasma Interaction



(b) Plasma-polished Surface

Fig. 13 Electron Microscope Photographs
(13,000s Magnification)

as laser pumping and the production of electron beams and electromagnetic pulses to name a few. For these reasons, a study of pulsed power techniques was carried out to provide a source of information on pulsed power to the scientific community [6].

A fundamental requirement of a pulsed power system is the rapid delivery of energy to the load at very high (GW or higher) power levels. These power levels are not available from the power grids. Thus, a system usually must accept and store energy at a low power level, then be discharged into a load at a high power level. The study addresses itself to several topics concerning the concepts of pulsed power. Among these are:

1) a brief introduction to some of the electrical terminology used.
2) a discussion of transformers, which are vital to many pulser schemes
3) an overview of switching requirements, primarily thyratrons, ignitrons, and spark gaps, with a brief discussion of the theory of operation of each.
4) a discussion of Marx generators
5) a report an fast risetime pulsers, including Blumlein generators, most of which are based on transmission line techniques.

This study also includes many useful equations and techniques concerning the use of the above mentioned devices. A full report has been prepared and transmitted to the AFOSR concerning

this study and the AFWL and Texas Tech University have printed and distributed some 400 copies of the report to the pulsed power community.

6. Conclusion

In summary, several projects have been carried out concerning the heating of plasmas and generation of X-rays and a study of pulsed power techniques used in the production and heating of such plasmas has been conducted. The prognosis for efficient X-ray production appears good for larger scale experiments utilizing some of the concepts presented here.

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